The Carbon Monoxide Tape Recorder

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Abstract

Using Aura MLS data we have identified the stratospheric 'tape recorder' in carbon monoxide (CO). Unlike the water vapor tape recorder, which is forced by the upper tropospheric seasonal variation in dehydration processes, the CO tape recorder is linked to seasonal changes in biomass burning. Since CO has a chemical lifetime of only a few months, the CO tape recorder barely extends above 20 km. The tape head for CO appears to be close to 360K near the same location as the water vapor tape head [Read et al, 2004]. Both tape heads are below the equatorial cold point tropopause but above the base of the tropical tropopause layer. The Global Modeling Initiative chemical transport model forced by the climatology of biomass burning reproduces the CO tape recorder. The tape recorder signal in the GMI model becomes more distinct from 360K to 380K suggesting that convective detrainment plays a decreasingly important role with altitude.
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1. Introduction

The identification of a tropical lower stratosphere temporal oscillation in the water vapor field was one of the most important discoveries of the Upper Atmosphere Research Satellite (UARS) [Mote et al., 1996, Randel et al., 2001]. Dubbed the "tape recorder" the UARS measurements showed that the seasonal variation of tropical water vapor concentration at the tropopause rises slowly into the stratosphere, and, although the amplitude of the signal decreases with altitude, it reaches to almost 35 km before being disrupted by the stratospheric semiannual oscillation. A similar tape recorder type signal is seen in aircraft CO_2 measurements [Andrews et al., 1999]. It would not be surprising if other tracers with seasonal variations in tropical forcing showed similar behavior. However, what is of special interest is the altitude of the base of the tape recorder or the "tape-head" because it bears on the theories of tropical dehydration.

Dehydration theories fall into two categories. Convective dehydration proponents argue that deep tropical convection rising to the cold-point tropical tropopause dehydrates air before entering the stratosphere [Newell and Gould-Stewart, 1981; Danielsen, 1982].

In this case the tape-head would be located at the cold point tropopause (CPT) at 375K (~17-17.5 km) [Gettelman and Forester, 2002]. Support for convective dehydration comes from observation of convective events overshooting the tropopause and from measurements of HDO/H_2O fractionation [Moyer, et al., 1996; Webster and Heymsfield, 2003] that show that the stratosphere is isotopically heavy. Ice formation depletes the isotope HDO from the surrounding air mass. Thus if the stratosphere is isotopically heavier than predicted by the Rayleigh fractionation curve, convection may be lofting isotopically heavy ice into the upper troposphere /lower stratosphere (UT/LS).

Alternatively, cold-trap dehydration proponents argue that the air is dehydrated as it slowly ascends through the upper troposphere [Brewer, 1949; Hartmann et al, 2001; Holton and Gettelman, 2001, Jensen and Pfister, 2004, Fuegistaler et al., 2005, and others]. In this case, the tape-head could be located below the cold-point tropopause, but this point may not necessarily be the location of the water vapor minimum. Read et al. [2004] using reprocessed UARS Microwave Limb Sounder (MLS) data noted that the water vapor tape-head appears to be located near 150-100 hPa - below the CPT.

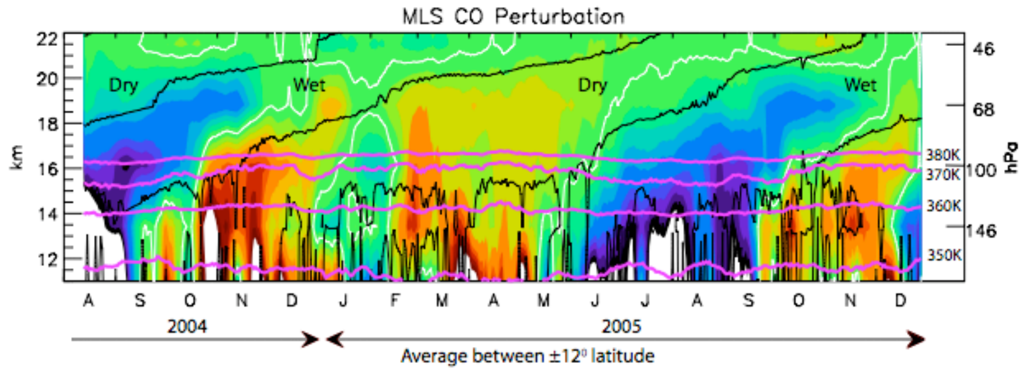
If the tape head is located below the cold point tropopause, as found by Read et al [2004], wouldn't convective mixing and detrainment disrupt the tape recorder? Sherwood and Dessler [2002] point out that since convective detrainment decreases rapidly with altitude it is possible for the tape recorder to be minimally impacted by convection between the tape head and the CPT, but convection could still act to dehydrate air in the upper tropopause [Sherwood and Dessler, 2000].

CO measurements provide an additional constraint on the transport of trace gases and water into the stratosphere. CO is lofted by deep tropical convection into the upper troposphere but, unlike H_2O, is not removed by condensation. Thus CO is a pure measure of transport processes.

Time variations of CO in the upper troposphere are due to a combination of the seasonal and spatial patterns of CO surface sources, especially agricultural burning [Duncan et al., 2003], and the seasonal movement of deep convection relative to the sources. In the troposphere, CO is produced by the oxidation of CH_4 and nonmethane hydrocarbons, and by incomplete combustion. It is predominantly removed by an oxidation reaction with OH [e.g., Levy, 1971; Crutzen, 1973].

2. MLS Observations of CO

The Aura MLS instrument and data are described in Waters et al. [2006] and the specifics of the level 2 data are described in JPL publication D-32381 available at http://mls.jpl.nasa.gov. CO is retrieved from the 240 GHz channel. The vertical resolution is about 4 km in the UT/LS.



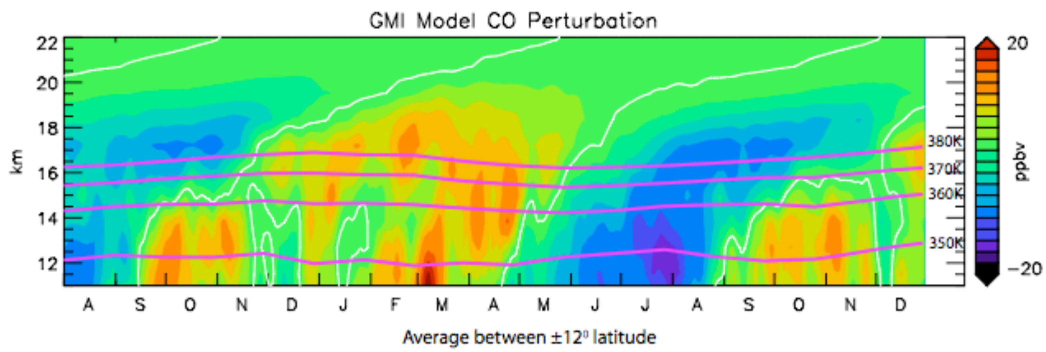


Figure 1. Part a, zonal mean MLS CO data with the annual average removed verses time (months). Altitude scale is 7 km log(1000/p) where p is pressure. Black lines show the zero contour for MLS water vapor tape recorder with 'wet' and 'dry' labels indicating the sign of the perturbation. White contours are zero lines for CO data. Right hand scale shows pressure levels for MLS level 2 data. Pink lines show the zonal mean potential temperature surfaces (350-380K). Part b, GMI chemical transport model CO simulation using climatological sources. The GMI chemical model is driven by the GEOS-4 GCM meteorology with1994-5 observed sea surface temperature forcing and has fixed water vapor amounts.

Fig. 1a shows the zonal mean MLS CO and H_2O data with the 2005 annual average removed. Data are area averaged between ±12^o latitude. Interpolating from nearby days fills in the occasional missing or bad data.

The figure shows a high degree of time variability below ~360K potential temperature (~14 km or ~130 hPa) associated with convective lofting of CO. There is no temporal shift between ~360K and lower altitudes as expected if the region was dominated by convective detrainment.

Above 360K CO and H_2O variations show ~1 month temporal phase lag with height between the two MLS levels 100 and 146 hPa. The zero phase lines show that the CO and H_2O have nearly the same phase change from 146 hPa up to 68 hPa identifying the structure of CO above 146 hPA as the CO tape recorder.

The zone where the phase shift begins is the tape-head. This is the zone above which convective detrainment is less important than diabatic uplift. The tape head for CO appears to be located at 360K and 375K although because of the resolution of the MLS data we cannot say exactly where. This location is below the CPT (375K or ~17.5 km) but above 350K (~13 km), usually considered to be the base of the tropical tropopause layer (TTL). The cloud-free diabatic heating rate changes sign at approximately 360K [Gettelman and Forster, 2002]. The UARS MLS H_2O observations also showed that that the "tape head" lies below the CPT but above the base of the TTL Read et al. [2004].

The CO tape recorder signal fades out above 20 km. Since the CO chemical lifetime is only 1-2 months at these altitudes the rapid decrease in CO abundance with altitude is expected.

To summarize, the CO tape recorder signal suggests that overall convection and detrainment in the TTL becomes less important than diabatic uplift above 360K. This result is also consistent with the assessment of tropical penetrating convection by Liu and Zipser [2005]. They note that only 1.3% of tropical convective systems reach 14 km and less than 0.1% reach 380K. But exceptions seem to occur. For example in February 2005 intermittent high values of CO appear above 380K connected to very high values below. In general, Fig. 1a shows that the tape recorder signal in both CO and H_2O is somewhat ragged between 360K and 380K suggesting that some regular disruption of the tape recorder by convection does occur [Dessler, 2002].

Fig. 1b shows the Global Modeling Initiative (GMI) Chemical Transport Model (CTM) simulation of CO averaged between ± 12° latitude. Water vapor is fixed in this model. The simulation uses meteorological variables from the GEOS-4 atmospheric GCM with 1994-6 sea surface temperatures (SST), although only mid-1994-1995 are shown in Fig. 1b, and climatological CO sources [Duncan et al., 2003]. Variation in tropical SSTs, especially associated with the ENSO phenomenon, drive much of the interannual variations observed in tropical convection. The period of MLS observations, mid-2004-5, experienced weak/moderate El Niño conditions until mid-2005 when weak La Niña conditions developed. These SST conditions were similar to the 1994-5 period.

A description of the GMI combined stratosphere-troposphere (COMBO) model can be found in Rotman et al. [2001] and Ziemke et al. [2006]. Convective transport is similar to that used in the MATCH model [Rasch et al., 1997]. GEOS-4 GCM meteorological fields [e.g., Bloom et al., 2005] are used as input to compute cloud mass fluxes, entrainment and detrainment fluxes, and large-scale downwelling. Both shallow and deep convection are considered, following the algorithms of Hack [1994] and Zhang and McFarlane [1995]. For the upper troposphere and lower stratosphere, Douglass et al. [2003] and Schoeberl et al. [2003] show that the large-scale circulation, including stratosphere-troposphere exchange (STE), is realistic in a CTM driven by the GCM fields.

Despite the different years represented by the observations and model, Figs. 1a and 1b show remarkable agreement. In the lower stratosphere, the tape recorder signal fades out at about the same altitude and the phase lines show roughly the same tilt. In the upper troposphere, the model simulates the variation in CO throughout the season.

This shows that the climatological forcing of surface CO emissions accounts for most of the variation in CO seen near the tropopause. The GMI model has higher vertical resolution in the TTL than the MLS data with an additional level between 146hPa and 100 hPa. The model shows the location of the tape head to be near 360K in rough agreement with the MLS data.

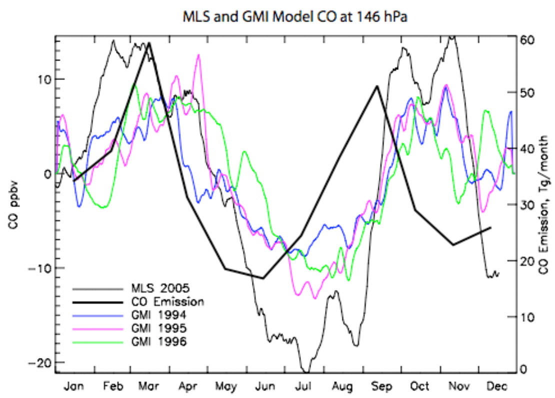


Figure 2. Comparison of three years of GMI model simulations (1994-6 SST) with 2005 MLS data at 146 hPA. Annual average has been removed. Also shown is the climatological biomass burning CO emission (30ºN-30ºS) used in the GMI model.

Fig. 2 shows a more detailed comparison between three years of GMI simulations and the 2005 CO observations from MLS at 146 hPa, roughly the altitude of the tape head. First, we note that the agreement between the model and the MLS observations is quite good. The two CO peaks are well simulated, but the GMI amplitudes are ~5-10 ppbv smaller than the observations. This could be due to weaker convective lofting and/or lower biomass burning emissions in the model than observed during the time of MLS measurements.

Comparing the climatological sources with the model and observed CO tells about which sources are feeding equatorial convection. Biomass burning CO is lofted by convection to the upper troposphere [Pickering et al., 1996] because of the proximity of the burning to large-scale monsoonal convection. Typically, fires are set preceding the arrival of seasonal rains to clear agricultural fields and pastures. The relatively long lifetime (~1 month) of CO allows its regional and zonal burdens to grow throughout the burning season, increasing the likelihood that biomass burning CO will encounter convective transport to the upper troposphere.

The first peak in the model CO emission (Fig. 2) is largely due to biomass burning in Indochina while the second peak is mostly due to southern Africa and Brazil [Duncan et al., 2003]. The first peak in the MLS CO perturbation is earlier than in the model though the second peak is fairly coincident, indicating that the timing of emissions in early 2005 is earlier than those in the model climatology consistent with observed fire counts. In some years the model CO remains elevated for a few weeks to more than a month after the decline in sources.

Figure 3 shows the 2005 MLS 146 hPa CO distribution for both peak periods. In Feb. and March, CO sources at the 146 hPa level are largely centered on equatorial Africa and Indonesia. In October and November CO sources are in southern Africa and Brazil. In June-August, CO at 146 hPa is elevated over northern India and southeast Asia, but this is north of the tape recorder region. At 215 hPa, the CO maps (not shown here) show additional hot spots over Central America and along the ITCZ stretching from the Philippines to Hawaii. Apparently convection over these regions does not systematically penetrate to the 146 hPa level in agreement with Liu and Zipser [2005].

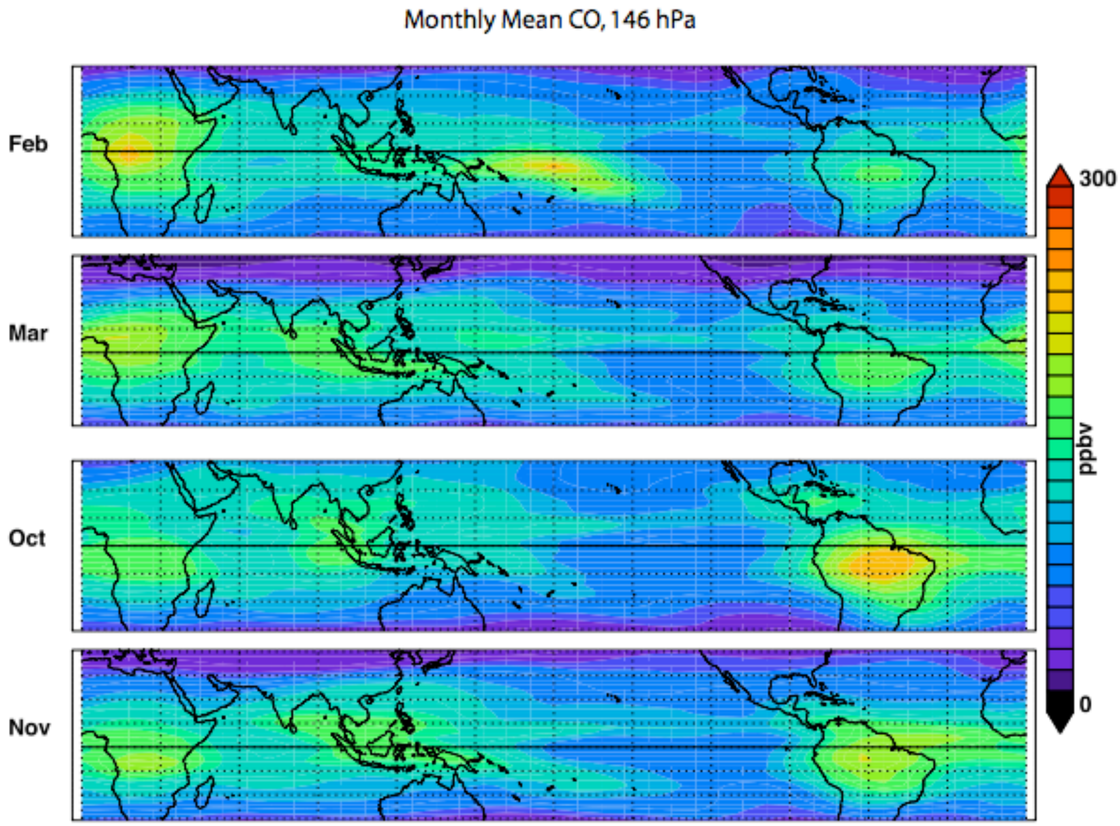


Figure 3 Monthly mean maps of MLS CO at 146 hPa for February, March, October and November.

3. Summary and conclusions

We have identified the UT/LS CO tape recorder in the MLS data. The CO tape recorder owes its existence to the seasonal variation in CO surface sources and tropical convective transport to the TTL. The head of the tape recorder is located between 360K and 375K in agreement with the location of the tape head in the UARS MLS H_2O [Read et al., 2004] and the Aura MLS H_2O data shown here. Simulations of the CO tape recorder using the GMI CTM show good agreement with the observations. The twice-yearly peak in CO at the tropopause is due to the north-south shift in biomass burning sources.

The MLS data and GMI model simulations suggests that large scale diabatic processes dominate convective above 360K (~100 hPa). The boundary between these two regions is not sharp; however, and there occasionally periods where detraining convection appears to penetrate much higher than 380K.

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